KESAN KADAR TERIKAN TERHADAP SIFAT-SIFAT TEGANGAN DAN PENENTUAN KELIATAN PATAH BAGI ALOI Mg-Al-Zn TERSEMPRIT

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TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEH IJAZAH DOKTOR FALSAFAH

FAKULTI KEJURUTERAAN DAN ALAM BINA
UNIVERSITI KEBANGSAAN MALAYSIA
BANGI

2015

DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

6 October 2015

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ACKNOWLEDGEMENT

Alhamdulillah, praise be to Allah, with give me a good healthy and strong heart to finish a degree of doctor philosophy in mechanical engineering at Universiti Kebangsaan Malaysia (UKM). I would like to express my sincerest thanks to my supervisor, Associate Professor Dr. Zainuddin Sajuri for giving the research opportunity and for his guidance, advices and motivations. I also would like to thank my co-supervisors and advisor, Associate Professor Dr. Syarif Junaidi from University of Sharjah, UAE and Prof. Dr. Yukio Miyashita and Prof. Dr. Yoshiharu Mutoh from Nagaoka University of Technology (NUT), Japan for their support and helpful discussion. Also, I wish to thank to Assoc. Prof. Dr. Yuichi Otsuka for his comment and suggestion while I am doing the research at NUT.

Consequently, I would like to express my high appreciation to Universiti Tun Hussein Onn Malaysia (UTHM) and Kementerian Pendidikan Malaysia (KPM) for sponsoring my study at UKM and NUT.

Not forget to thank laboratory technicians from UKM, Mr Firdaus, Mr Faizal and Mr Jamaluddin and laboratory technician from NUT, Mr Hosokai that always assist me for preparing specimen, setting the test machine and conducting the test.

I also would like to thank all my friends from UKM, NUT and UTHM for their friendship and support.

Lastly, special thanks to my beloved family, hubby, daughter and parents for their continuous support, understanding and encouragement.

ABSTRACT

Extruded Mg-Al-Zn alloy is a lightweight and high strength magnesium alloy that is becoming a preferred material to be used as a structural component in automobiles. During a crash event, an automobile structure is subjected to dynamic loading. The magnesium alloy structures must be able to maintain its integrity and provide adequate protection in survivable crashes. Besides static tensile properties, tensile properties at high strain rates of extruded magnesium alloys and their fracture behaviour are some of the important parameters to be considered in design in ensuring the durability and reliability of automobile structures. In this study, the effect of strain rates on tensile properties and work hardening behaviour were evaluated for extruded Mg-Al-Zn alloys. Further, the fracture behaviour at different loading rates and the effect of temperature on fracture toughness of Mg-Al-Zn alloys were investigated. The extruded Mg-Al-Zn alloys used in this study were AZ61 and AZ31 magnesium alloys. Tensile tests under low and high strain rates were carried out using a universal testing machine and high strain rate tensile tester, respectively. The high strain rate tensile tester was designed and fabricated in-house to fulfil the requirement of tensile test under high strain rate ranging from 100 to 600 s^{-1}. Work hardening behaviour for low strain rate tensile specimen was determined by referring to the ASTM E646. To obtain the fracture behaviour of both alloys at different loading rates, three-point bending fracture test was conducted on pre-cracked specimens. Standard test methods i.e. ASTM E1820 and JSME S001 were referred to determine the elastic-plastic fracture toughness J_{IC} value of AZ31 and AZ61 alloys. The J_{IC} value obtained were then used as a standard reference value to identify a proper groove depth of a single side-grooved specimen. The side-groove depths evaluated were 25%, 35% and 50%. The proper depth of the side-grooves is confirmed after the J value obtained from the side-grooved specimen test method is identical to the J_{IC} value that of the standard test method. The side-grooved specimen with proper groove depth was then used to determine the J_{IC} value of AZ61 alloy at high temperature. From the results, the tensile strengths were gradually increased with increasing strain rates. However, at above 200 s^{-1}, the tensile strength increased significantly to more than 600 to 800 MPa. In addition, the work hardening rate for AZ61 was found higher compared to that of AZ31. Both alloys exhibited significant elastic-plastic fracture behaviour at different loading rates. It was found that 50% side-grooves depth is appropriate enough to produce valid J_{IC} value using a single specimen. This finding is very useful especially in determining J_{IC} value in a condition where standard multiple specimen test method is difficult to be conducted such as in high temperature environment. The J_{IC} values of AZ31 and AZ61 at room temperature were 19 and 25 kJ/m^2, respectively. Meanwhile, the J_{IC} value of AZ61 at 150 °C was found twice higher than the J_{IC} value at room temperature.

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ABSTRAK

Aloi Mg-Al-Zn tersemperit merupakan aloi magnesium yang ringan dan berkekuatan tinggi yang makin menjadi bahan pilihan untuk digunakan sebagai komponen struktur dalam kenderaan. Semasa kemalangan, struktur kenderaan dikenakan dengan beban dinamik. Struktur daripada aloi magnesium mestilah berupaya dalam mengekalkan integriti dan memberi perlindungan yang secukupnya semasa kemalangan. Selain sifat-sifat tegangan statik, sifat-sifat tegangan pada kadar terikan yang tinggi aloi magnesium tersemperit dan sifat patahnya adalah parameter penting yang perlu dipertimbangkan dalam rekabentuk bagi memastikan ketahanan dan kebolehpercayaan pada struktur kenderaan. Dalam kajian ini, kesan kadar terikan terhadap sifat-sifat tegangan dan sifat pengerasan kerja telah dinilai bagi aloi Mg-Al-Zn tersemprit. Seterusnya, sifat patah pada kadar pembebanan berbeza dan kesan suhu terhadap keliatan patah bagi aloi Mg-Al-Zn telah dikaji. Aloi Mg-Al-Zn tersemprit yang digunakan dalam kajian ini adalah aloi magnesium AZ31 dan AZ61. Ujian tegangan pada kadar terikan rendah dan tinggi telah dijalankan dengan masing-masing menggunakan mesin ujian semesta dan mesin ujian kadar terikan tinggi. Mesin ujian kadar terikan tinggi telah direka dan dibangunkan sendiri untuk memenuhi keperluan ujian tegangan pada kadar terikan tinggi di antara 100 sehingga 600 s^{-1}. Sifat pengerasan kerja untuk spesimen tegangan pada kadar terikan rendah telah ditentukan dengan merujuk kepada ASTM E646. Bagi memperolehi sifat patah kedua-dua aloi pada kadar pembebanan yang berbeza, ujian patah tiga-titik lenturan telah dijalankan pada spesimen pra-retak. Kaedah ujian piawai iatu ASTM E1820 dan JSME S001 telah dirujuk untuk menentukan nilai J_{IC} keliatan patah elastik-plastik bagi aloi AZ31 dan AZ61. Nilai J_{IC} yang diperoleh kemudiannya digunakan sebagai nilai rujukan piawai untuk mengenalpasti kedalaman alur yang wajar pada satu spesimen sisi beralur. Kedalaman sisi beralur yang dinilai adalah 25%, 35% dan 50%. Kedalaman wajar bagi sisi alur disahkan selepas nilai J yang diperolehi daripada kaedah ujian spesimen sisi beralur adalah sama dengan nilai J_{IC} daripada kaedah ujian piawai. Spesimen sisi beralur dengan kedalaman alur yang wajar kemudiannya digunakan untuk menentukan nilai J_{IC} bagi aloi AZ61 pada suhu tinggi. Daripada keputusan, kekuatan tegangan meningkat secara perlahan dengan peningkatan kadar terikan. Bagaimanapun, pada kadar melebihi 200 s^{-1}, kekuatan tegangan meningkat dengan ketara melebihi dari 600 hingga 800 MPa. Di samping itu, kadar pengerasan kerja untuk AZ61 didapati tinggi berbanding AZ31. Kedua-dua aloi mempamerkan sifat patah elastik-plastik yang ketara pada kadar pembebanan yang berbeza. Didapati 50% kedalaman sisi alur adalah cukup sesuai untuk mendapatkan nilai J_{IC} yang sah menggunakan hanya satu spesimen. Penemuan ini amat berguna terutamanya bagi menentukan nilai J_{IC} dalam keadaan di mana kaedah ujian piawai berbilang spesimen adalah sukar untuk dilakukan seperti dalam persekitaran suhu yang tinggi. Nilai-nilai J_{IC} bagi AZ31 and AZ61 pada suhu bilik adalah masing-masing 19 dan 25 kJ/m^2. Sementara itu, nilai J_{IC} bagi AZ61 pada 150 °C didapati dua kali lebih tinggi berbanding nilai J_{IC} pada suhu bilik.

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NOMENCLATURE

Symbols

a	crack length
Δa	crack growth
$\frac{da}{dN}$	fatigue crack growth rate
A	area
A_o	original cross section area of test specimen
A_i	final cross section area of test specimen
A_T	area of cross section at force
A_{max}	area under the curve up to maximum load (P_{max}) point
$A_{specimen}$	actual area under the curve of testing specimen
A_{total}	total area under the curve of test
A_{jig}	area under the curve of testing jigs
b	remaining crack ligament
B	specimen thickness
B_N	net specimen thickness
B_e	effective thickness
B_{e1}	effective thickness 1
B_{e2}	effective thickness 2
B_{e3}	effective thickness 3
β	second phase
d	displacement
d_1	length of long diagonal
d_s	side-grooves depth

ds	increment of the countour path
E	Young's modulus
F	force
$f(\alpha)$	geometry factor
g	acceleration of gravity (9.81 m/s^2)
h	drop weight height
J	J-integral
J_C	critical J-integral
J_{IC}	fracture toughness J_{IC}
K	stress intensity factor
K_s	strength coefficient
K_Q	critical stress intensity factor
K_I	mode I stress intensity factor
K_{Id}	dynamic fracture toughness
K_{IC}	fracture toughness K_{IC}
ΔK	stress intensity factor range
K_m	mean stress intensity factor
K_{min}	minimum stress intensity factor
K_{max}	maximum stress intensity factor
L_o	original gage length
L_f	final gage length
dL	increment of elongation
m	mass
$Mg_{17}Al_{12}$	precipitation

n	strain hardening exponent
P	load
P_Q	critical load
P_5	load at intersection of 95% slope on load-displacement curve
P_{max}	maximum load
P_y	load point at 0.2% offset from the linear slope on load-displacement curve
R	stress ratio
S	span length
Δs	displacement of loading points
T	outward traction vector on *ds*
u	displacement vector at *ds*, *x*, *y*, *z* of the rectangular coordinates
v	impact velocity or high strain rate
w	loading work per unit volume
W	specimen width
W_P	work done
Y	geometry factor
ε	elongation
ε_T	true strain
ε_e	true elstic strain
ε_P	true plastic strain
$d\varepsilon_T$	increment of true plastic strain
σ_y	yield stress
σ_{UTS}	tensile strength

σ_f	flow stress
σ_C	critical stress
σ_T	true stress
$d\sigma_T$	increment of true stress
Γ	path of the integral around the crack tip
$T\left(\frac{\partial u}{\partial x}\right)ds$	work input rate from the stress filed into the area enclosed by Γ

Abbreviations

HCP	hexagonal close packed
CRSS	critical resolved shear stress
UTM	universal testing machine
LVDT	linear variable differential transformer
MSDS	material safety data sheet
CT	compact tension
SENB	single edge notched bending
EDM	electrical discharge machining
ASTM	American society for testing and materials
JSME	Japan society of mechanical engineers
LEFM	linear elastic fracture mechanics
EPFM	elastic-plastic fracture mechanics
SEM	scanning electron microscope
SHPB	split Hopkinson pressure bar

Chapter I

INTRODUCTION

1.1 RESEARCH BACKGROUND

Magnesium alloys have been attractive to engineers due to their lightweight and high specific strength properties as compared to aluminium and medium-strength steel alloys (Smith 1998). The specific strength of alloys is measured based on the strength to the weight ratio, while the lightweight property refers to the density of alloys. In this regard, magnesium alloys have been used in electric and electronic appliances as well as automotive applications. In automotive applications, these parameters are beneficial to reduce fuel consumption, enhance the energy efficiency of engines and reduce emissions. In addition, magnesium alloys are also excellent in machinability, castability, recyclability and high damping capacity. Hence, magnesium alloys attract the automobile manufacturers to use these alloys as components and structures for replacing the conventional materials such as steel, cast iron and aluminium (Gaines 1995; Mordike & Ebert 2001; Kainer 2003; Watarai 2006). Magnesium has been used since the 1930s in the Volkswagen (VW) Beetle. Nowadays, automobile manufacturers such as Volkswagen, Audi, DaimlerChrysler (Mercedes-Benz), Toyota, Ford, BMW, Jaguar, Fiat, Hyundai, and Kia Motors Corporation generally use magnesium alloys as components and structures (Gupta & Sharon 2011). However, utilisation of magnesium alloys in automotive applications is still limited compared to that of conventional materials (Luo 2002).

The most popular magnesium alloys used as automobile components and structures are AZ (Mg-Al-Zn), AM (Mg-Al-Mn), ZK (Mg-Zn-Zr) and WE (Mg-Y-RE) series magnesium alloys. This is due to the best properties of magnesium alloys for certain applications are governed by the combination of alloying element contents. In the present study, Mg-Al-Zn series magnesium alloys have been used. The main elemental contents of Mg-Al-Zn alloys are aluminium and zinc. These main elements are beneficial for enhancing the strength of alloys (Kainer 2003). In addition, Mg-Al-Zn alloys are characterised as low cost, a good strength and good ductility alloy. Due to its ductile property, Mg-Al-Zn alloys are easy to produce in the shape of extruded and simple forged products. Therefore, extruded and simple forged products of Mg-Al-Zn alloys are used as components and structures in automobile applications (Becker & Fischer 2004).

Mechanical properties are referred to when choosing a good potential material especially for application in automobile concerned with the safety parameter and quality assurance. Mechanical properties comprise hardness, tensile properties, flexural strength, fracture toughness etc. Excellent mechanical properties refer to the potential material related to the durability and reliability of materials. In the present study, the potential materials such as Mg-Al-Zn alloys are beneficial for use in automobile applications to prevent or reduce the impact of critical damage in the case of accident. Mg-Al-Zn alloys are also ductile material (Becker & Fischer 2004) beneficial in automobile applications to prevent or reduce the critical crashes due to high energy absorption capability. However, application of Mg-Al-Zn alloys in extreme conditions is believed to give influenced on the mechanical properties. In general, extreme conditions are referred to the condition such as high loading rate, impact loading response, elevated temperature conditions etc. Tensile strength is significantly strain rate dependent for many materials. At the same time, tensile strength is also temperature dependent for pure and magnesium alloys (Chino 2002; Feng et al. 2014; Kim & Chang 2011; Ulacia et al. 2011). In case of accident, a high loading rate with impact response is significantly applied to the vehicle. Elevated temperature is commonly subjected to automobile components and structures since the powertrain applications such as transmission cases are operated up to 175 °C, while the engine blocks and engine pistons up to 200 °C and 300 °C, respectively (Luo 2002; Luo 2004; Gupta & Sharon 2011). Therefore, engine surrounding temperatures could rise up to more than 100 °C. Hence, knowing the effect of extreme conditions on mechanical properties is for Mg-Al-Zn alloys are important.

1.2 PROBLEM STATEMENT

As mentioned, magnesium alloys have several advantages when used as components and structures in automobile applications. However, the utilisation of magnesium alloys in automobile applications is still limited compared to that of conventional materials (Luo 2002). This is because the conventional used are of significantly high strength materials beneficial for reducing or preventing critical crashes during accidents. Consequently, studies in obtaining the mechanical properties of those materials are also widely reported (Mutoh 1987; Yi & Xiao-Wei 1988; Kobayashi et al. 1997; Zhang & Shi 1992; Kong et al 2011). Thus, many automotive manufacturers are still using conventional materials in automotive applications.

Several series magnesium alloys are used in automotive application. For example, car body parts, crankcase, seat frame and wheel are made from AZ31, AZ91, AM60 and ZK30 magnesium alloys, respectively (Fink 2003; Friedrich & Mordike 2006; Becker & Fischer 2003). Commonly, these components and structures are subjected to high and different velocities, impact loads and then critical crash during accident. Hence, mechanical properties of magnesium alloys under impact response are required to refer prior to applying the potential magnesium alloys in automotive applications. In addition, it is important to understand these impact fracture properties to understand the material response after being subjected to similar actual situations during accident. However, in previous studies, most mechanical properties are reported under testing at static response and fatigue loads in the case of vibration in service applications (Chamos et al. 2008; Somekawa et al. 2008; Khan et al. 2006). Moreover, these fracture properties are not appropriate for crash design and impact fracture properties are preferable.

For magnesium alloys, mechanical properties of these alloys such as hardness and tensile properties are well known. In previous studies, many researchers reported

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